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# Dredging for edible cockles (*Cerastoderma edule*) on intertidal flats: short-term consequences of fisher patch-choice decisions for target and non-target benthic fauna

Casper Kraan, Theunis Piersma, Anne Dekinga, Anita Koolhaas, and Jaap van der Meer

Kraan, C., Piersma, T., Dekinga, A., Koolhaas, A. and van der Meer, J., 2007. Dredging for edible cockles (*Cerastoderma edule*) on intertidal flats: short-term consequences of fisher patch-choice decisions for target and non-target benthic fauna. – ICES Journal of Marine Science, 64: 1735–1742.

Intertidal flats in the Dutch Wadden Sea are protected by national and international treaties. Still, mechanical dredging for edible cockles *Cerastoderma edule* was allowed in 74% of 1200 km<sup>2</sup> of intertidal flats. Cumulatively, between 1992 and 2001, 19% of the intertidal area was affected by mechanical cockle-dredging at least once. On the basis of a grid of 2650 stations sampled annually, we evaluate the extent to which cockle-dredging from 1998 to 2003 was selective with respect to non-target macrozoobenthic intertidal fauna. In all 4 years that comparisons could be made, to-be-dredged areas contained greater diversity of macrobenthic animals than areas that remained undredged. Targeted cockles were 2.5 times more abundant in areas that were to be dredged shortly, but other species also occurred in higher densities in these areas. Small amphipods and some bivalves occurred less in to-be-dredged areas than elsewhere. In terms of short-term responses to dredging, four non-target species showed a significant decrease in abundance 1 year after dredging. Only *Tellina tenuis* showed an increase a year after dredging.

**Keywords:** cockle-dredging, intertidal macrozoobenthos, patch-choice, short-term effects, Wadden Sea.

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## Introduction

Large-scale industrial fishing such as trawling or dredging for demersal marine fauna is increasingly seen as a threat to the world's marine biota (Roberts, 1997; Watling and Norse, 1998; Jackson, 2001; Coleman and Williams, 2002; Dayton, 2003; Rosenberg, 2003; Blundell, 2004). There is considerable evidence for short- and long-term negative effects of trawling and dredging on populations of target and non-target species (Jones, 1992; Dayton *et al.*, 1995; Jennings and Kaiser, 1998; Collie *et al.*, 2000; Piersma *et al.*, 2001; Kaiser *et al.*, 2006). However, management of such fisheries is often based on sustainable use of the stock of the target species only, without application of a more comprehensive ecosystem approach that includes non-target species (Turner *et al.*, 1999; Murawski, 2000).

Since the late 1980s and as a continuation of old fishing rights, in most years industrial harvesting of edible cockles (*Cerastoderma edule*) and blue mussels (*Mytilus edulis*) was allowed in 75% of the intertidal flats in the Dutch Wadden Sea, a 2400 km<sup>2</sup> area of barrier islands, shallow waters, and intertidal flats (Abrahamse *et al.*, 1976; van de Kam *et al.*, 2004). These areas have been designated by the Dutch government as a State Nature Monument and Protected Nature Area. The Wadden Sea as a whole is protected under the European Commission's Bird and Habitat Directives, has Ramsar as well as Man and Biosphere (United Nations Educational, Scientific and Cultural Organization) status, and

is a Particular Sensitive Sea Area under the International Maritime Organization of the United Nations. Although the scientific community voiced concern (Piersma *et al.*, 1993a, Piersma and Koolhaas, 1997, 2001; Kareiva and Laurance, 2002; and see Swart and Van Andel, 2007, for a historical review of the conflict), the government of the Netherlands assessed single-species stock status only (Smit *et al.*, 1998; Kamermans and Smaal, 2002).

Here, we document "patch-choice decisions" by mechanical cockle-dredgers, at the scale of the actual fisheries, not only with respect to the target species (*C. edule*), but also for non-target macrobenthic species. Our assessment is based on six benthic surveys carried out between 1998 and 2003 that were done just before the cockle-dredging season, covering >170 km<sup>2</sup> of intertidal flats in the western Dutch Wadden Sea. Further, we evaluate short-term effects (1 year later) on local density by way of paired comparisons between neighbouring dredged (impact) and undredged (control) areas.

By matching neighbouring impact and control areas on the basis of abiotic characteristics, the absence of randomly appointed treatment and control areas, because of the non-random distribution of dredging effort, was controlled for. In this way, spatial and temporal variation between control and impact area were (as far as possible) minimized. Finally, we examine whether changes in the abundance of various benthic species attributable

to dredging is proportional to the selectivity exerted on them by the cockle-dredgers.

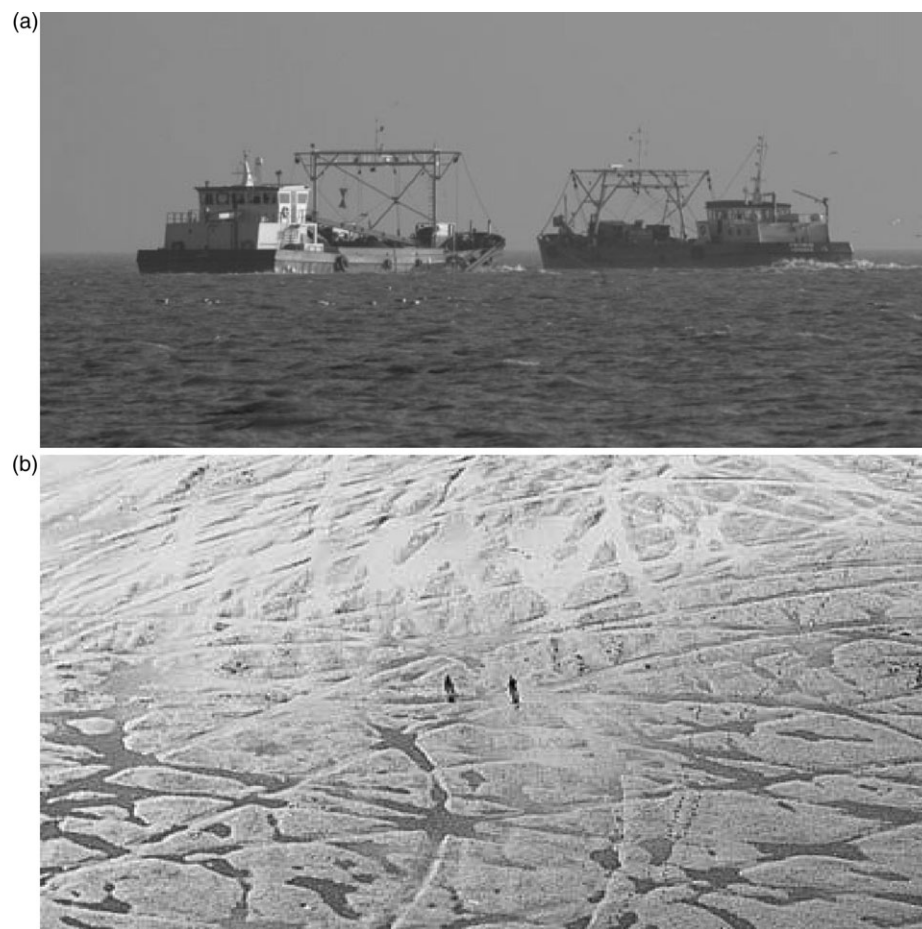
### Dutch cockle-dredging

From 1993, following serious winter starvation of common eiders (*Somateria mollissima*) and European oystercatchers (*Haematopus ostralegus*) (Smit *et al.*, 1998), 26% of the intertidal area in the Dutch Wadden Sea was closed to mechanical cockle-dredgers, with an additional 5% closed between 1998 and 2001. Reflecting the abundance or scarcity of cockles, the number of ships actively employed varied between a maximum of 22 and a minimum of 3 (in 2003).

Suction-dredging takes place when the mudflats are covered with a minimum of 80 cm of water (Figure 1a). The dredges (75 or 125 cm wide) have a water jet in the front to loosen the top layer of the sediment, which is then scraped off by a blade at a depth of ~5 cm. Within the dredge, a strong water flow ensures that objects with a diameter <15 mm are pushed through a screen. The remaining larger objects are sucked on board the ship for further cleaning and handling. Cockle-dredgers aim at cockles >19 mm, the minimum size for consumption. After dredging, the intertidal flats appear “scarred” (Figure 1b), and can remain so for a whole winter (De Vlas, 2000; Ens *et al.*, 2004).

To record position and fishing activity, mainly as an internal control, a “black-box” system (a GPS logger) was operated on board every vessel by the Association of Mechanical Cockle Dredgers based in Kapelle (Kamermans and Smaal, 2002). Cumulative seasonal data from the black boxes are screened and edited internally by the Association, which then releases maps with coloured blocks of 0.1' of latitude by 0.5' of longitude. Blocks are only coloured if >2% of the surface is touched by the dredge. Therefore, in many cases, sampling points to be dredged would not have been touched. This means that our assessment of dredging effects is conservative; i.e. a lack of statistical effects does not necessarily imply lack of ecological effects.

The Association presents an annual value for the total surface area of the tracks, a value corrected for overlap. On average, 4.3% of 1200 km<sup>2</sup> of the intertidal flats in the Dutch Wadden Sea (Wolff, 1983) was reported to be affected annually by dredging from 1998 to 2000 (Donkers, 1998, 2000; Huijssen 2001). When converted to actual fishing tracks, an average of 1.3% of the surface of intertidal flats would have been dredged each year (Kamermans *et al.*, 2003). Cockle beds were often dredged in consecutive seasons; 54% of all dredged stations examined here ( $n = 710$ ) were dredged once between 1998 and 2003, but 25% were dredged twice during the period, 14% three times, and 7% were dredged every year.



**Figure 1.** (a) Cockle dredgers in action near Vlieland, November 2002 (photo M. de Jonge). (b) Aerial view of the surface scars of cockle dredging. For scale, note the two human figures (photo J. de Vlas).

## Material and methods

### Study area

The study area covers a large part of the western Dutch Wadden Sea (Figure 2). With a tidal amplitude of 1.5 m at neaps, to 2 m at spring tides, it encompasses an area of 890 km<sup>2</sup> of intertidal flats. The area is partitioned by three main tidal channels separating the mainland and the barrier islands of Texel, Vlieland, and Terschelling. The sediment consists of sands and muddy sands, with median grain sizes ranging from 140 to 200 µm (Piersma *et al.*, 2001; Zwarts *et al.*, 2003). Between 1989 and 1991, all natural beds of mussels were removed mechanically from the study area (Piersma *et al.*, 1993b; Smit *et al.*, 1998; Ens, 2003).

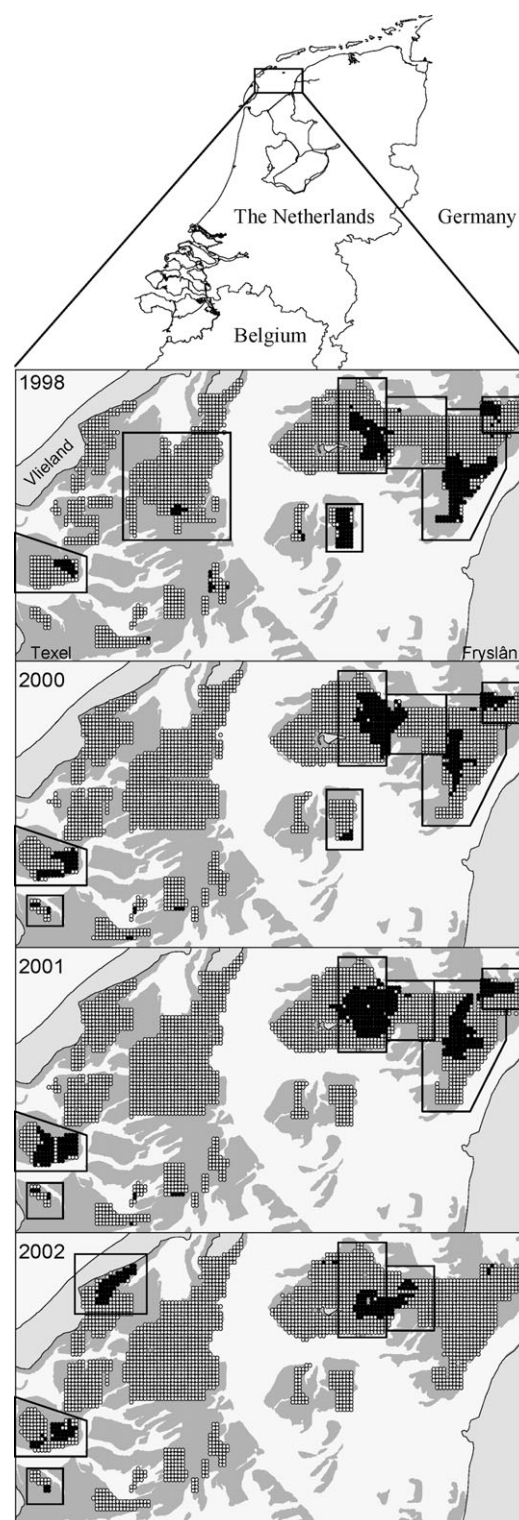
Some 170 km<sup>2</sup> of the study area is covered with a grid of fixed sampling stations 250 m apart (Figure 2). Except for a nearshore area just south of Vlieland that was closed in 1999 and reopened in 2002, mechanical dredging was allowed everywhere. In 1998, 2000, 2001, and 2002, respectively, 14.9%, 11.5%, 15.4%, and 8.0% of our sampling stations were dredged (Figure 2). In 1999, virtually all fishing was in the eastern part of the Dutch Wadden Sea. The cumulative area affected by dredging from 1992 to 2001 was 19% of the whole Dutch Wadden Sea (Kamermans *et al.*, 2003); in our study area, this was 24.6% from 1998 to 2002.

### Sampling routines

Sampling stations were visited either on foot or by boat once a year between mid-July and early September. Although fishing was permitted from mid-August on, dredging never started before early September and continued to December (or even as late as January/February in the 2002/03 season). From 1998 to 2003 we sampled, respectively, 2326, 2539, 2731, 2749, 2762, and 2680 stations. These surveys, carried out independently of the fishery, aimed at documenting benthic food abundance to gain an understanding of shorebird distributions (Van Gils *et al.*, 2005, 2006a).

Sampling stations were found with hand-held GPS (Garmin 45 and 12, using WGS84 as map datum), and at each station one (on foot) or two (by boat) sediment cores, covering 0.018 m<sup>2</sup> in total, to a depth of 20–25 cm were taken. The cores were sieved over a 1 mm mesh and numbers of all species were recorded; for bivalves, the age/size classes were also noted. All crustaceans and molluscs were collected and stored at –20°C for later analysis in the laboratory (see Piersma *et al.*, 1993b; Van Gils *et al.*, 2006a, b, for details). On average, 56% of the samples were taken by boat and 44% on foot. Both methods, based on comparisons between benthos densities at 165 adjoining positions (excluding *Hydrobia ulvae*) that were either sampled by boat or on foot between 1998 and 2004, yield similar results (unpublished data).

An invasion of the exotic polychaete *Marenzelleria viridis* began about 1998, but quantitatively we only trust and subsequently use observations from 2000 on. Rare species such as the tube-living polychaete *Lagis koreni* were excluded from analysis. Their scarcity made comparisons between control and impact areas impossible. The mudsnail *H. ulvae* was also excluded, because numbers were not sampled quantitatively by boat. Note that cockles were separated into two size classes, ≤19 and >19 mm, and subsequently treated as separate species in the analysis.



**Figure 2.** Sampling grid in the western Dutch Wadden Sea and the extent of mechanical cockle-dredging in autumn of 1998, 2000, 2001, and 2002. Dredged sampling stations are indicated by a filled dot, sampling stations not potentially affected by mechanical dredging by open circles. For each year, paired sampling areas with dredged and undredged quadrants, used to determine species' response to dredging, are indicated by boxes. Year 1999 is not shown, although benthic sampling was carried out, because that year all commercial dredging took place in the eastern Wadden Sea.



### Statistical analysis

We tested for differences in the number of species per station (target-sized cockles excluded) between the to-be-dredged area and the undredged area for the whole western Dutch Wadden Sea, by Student's *t*-tests on log-transformed data. This procedure assumes that cores taken 250 m apart are independent samples. Data from four dredging seasons (1998, 2000, 2001, and 2002) were included.

We also determined whether cockle-dredging led to changes in the abundances of macrozoobenthic species, *a posteriori* matching dredged (impact) areas with undredged neighbouring ones (control areas). We made sure that paired areas were similar in terms of tidal height, water coverage during high tide, and sediment composition, to ensure that temporal as well as spatial effects would be accounted for statistically (Figure 2). Historically, industrial cockle-dredging started in the 1950s, with strong growth in the 1970s (Dijkema, 1997). Therefore, undredged areas only refer to areas not dredged during this study. However, all areas are likely to have been affected by dredging in the previous 20 years (Zwarts *et al.*, 2003). The relative occurrence of a particular species before dredging (Table 1) is computed as the ratio of the density in to-be-dredged to undredged areas (Figure 2),

$N_{d0}/N_{c0}$ , where  $N$  denotes average density (averaged over all areas) of the focal species, and  $d$  and  $c$  designate dredged or control areas. Zero indicates before dredging and a numeral 1 to the densities 1 year after dredging.

To detect changes in density attributable to cockle-dredging, we examined densities in paired areas after dredging, i.e. using the benthic data up to and including 2003. The changes in density attributable to dredging in autumn 1998 were then calculated with data from 1999, using stations sampled in both years only. This fisheries effect was calculated as  $\ln(N_{d1}/N_{c1})$ . In the absence of any effect of cockle-dredging, the relative occurrence and the fishery effect are expected to be the same, i.e.  $\ln N_{d0}/N_{c0} = \ln N_{d1}/N_{c1}$ . The null hypotheses of no fishery effect was tested with 1000 bootstrap samples (Manly, 1997) of paired control ( $N_{c1}$ ) and impact ( $N_{d1}$ ) average densities after dredging and before dredging ( $N_{d0}$  and  $N_{c0}$ ). This generated 1000 combinations of dredging-related alterations and the accompanying selectivity index ( $N_{d0}/N_{c0}$ ) for each species. Average densities were based on paired area combinations; 25 in total over all years (Figure 2). Observed values were then compared with bootstrapped values (Manly, 1997). Statistical analyses were performed with either SYSTAT or R (R Development Core Team, 2006).

**Table 1.** Relative occurrence averaged overall dredging seasons of target (large *C. edule*) and 20 non-target species (including *C. edule*  $\leq 19$  mm as a category) at intertidal sampling stations in the western Dutch Wadden Sea, based on the paired control and impact areas shown in Figure 2.

Species	Taxon	Relative occurrence (dredged/undredged)	Density-change direction attributable to dredging	<i>p</i> -value
Target species				
<i>Cerastoderma edule</i> > 19 mm	Bivalvia	2.52	–	0.005*
Non-target species				
<i>Mytilus edulis</i>	Bivalvia	12.81	–	0.004*
<i>Heteromastis filiformis</i>	Polychaeta	1.77	–	0.003*
<i>Phyllodoce mucosa</i>	Polychaeta	1.58	+	0.32
<i>Nereis diversicolor</i>	Polychaeta	1.41	–	0.13
<i>Nephtys hombergii</i>	Polychaeta	1.37	–	0.17
<i>Ensis americanus</i>	Bivalvia	1.28	–	0.02*
<i>Arenicola marina</i>	Polychaeta	1.24	+	0.22
<i>Macoma balthica</i>	Bivalvia	1.17	–	0.24
<i>Crangon crangon</i>	Decapoda	1.10	–	0.025*
<i>Lanice conchilega</i>	Polychaeta	1.08	0	0.54
<i>Carcinus maenas</i>	Decapoda	0.98	–	0.21
<i>Eteone longa</i>	Polychaeta	0.95	0	0.83
<i>Cerastoderma edule</i> $\leq 19$ mm	Bivalvia	0.87	+	0.07
<i>Marenzelleria viridis</i>	Polychaeta	0.85	–	0.10
<i>Mya arenaria</i>	Bivalvia	0.78	0	0.71
<i>Scoloplos armiger</i>	Polychaeta	0.72	0	0.67
<i>Gammarus locusta</i>	Amphipoda	0.71	+	0.27
<i>Urothoe</i> sp.	Amphipoda	0.69	0	0.63
<i>Corophium volutator</i>	Amphipoda	0.48	–	0.39
<i>Abra tenuis</i>	Bivalvia	0.27	–	0.47
<i>Tellina tenuis</i>	Bivalvia	0.11	+	0.001*

Non-target species were arranged according to the value of the ratio of dredged to undredged. The direction of change, increase (+), decrease (–), and no change (0), is shown. Changes in density over 1 year were tested by bootstrapping. The asterisks indicate significance.

## Results

Sampling points that were to be dredged had on average 25% more macrozoobenthic species (target-sized cockles excluded) than eventually undredged stations (Figure 3) (Student's *t*-test,  $t = 4.65$ , d.f. = 8,  $p < 0.01$ ). The Shannon–Wiener index, based on  $\log(x + 1)$ -transformed abundances, gave similar results ( $p < 0.01$ ), with mean values for to-be-dredged areas between 0.48 and 0.53, and for undredged areas varying between 0.37 and 0.43. This means that from 1998 to 2002, cockle-dredgers concentrated their fishing in intertidal areas with relatively high macrozoobenthic species diversity.

Using the paired comparisons between undredged and to-be-dredged parts of the otherwise similar intertidal areas (Figure 2), targeted *C. edule* (>19 mm length) were 2.5 times more abundant in the area to be dredged later that season (Table 1). *Mytilus edulis* was 12.8 times more abundant, *Nereis diversicolor* 1.4 times, *Ensis americanus* 1.3 times, and *Macoma balthica* 1.2 times (Table 1). Species that occurred less in to-be-dredged areas than elsewhere were mainly small amphipods, polychaetes such as *Scoloplos armiger*, and the bivalves *Abra tenuis* and *Tellina tenuis* (Table 1).

Mechanical dredging for cockles had a significant negative short-term effect on the abundance of five species and a positive effect for one species, which corresponds to 27% of the intertidal benthic species examined (Table 1, Figure 4). However, the relationship between fishery effect and relative occurrence could be characterized as fuzzy (Figure 4). The abundance of most species seemingly neither increased nor decreased after 1 year proportional to their relative occurrence in dredged areas. Not surprisingly, consumption-size cockles showed a density reduction by cockle-dredging on top of natural mortality. The same effect was present for *M. edulis*, *Heteromastis filiformis*, *Crangon crangon*, and *E. americanus*, even if the last three were not in particularly high densities in dredged areas. Small cockles ( $\leq 19$  mm), *Carcinus maenas*, and the polychaete *M. viridus* revealed no additional negative or positive fishery effect. Only *T. tenuis* demonstrated a significant increase in abundance after dredging.

## Discussion

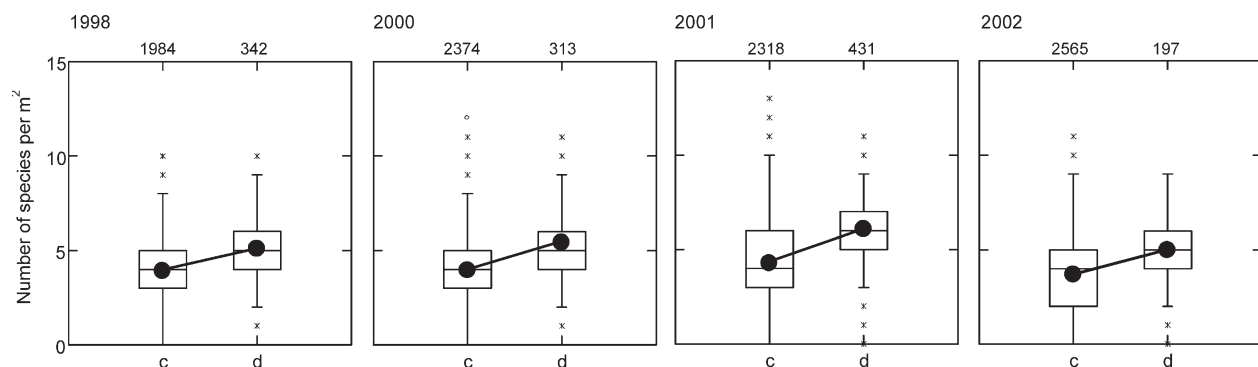
Most research dealing with fisheries effects necessarily describes ecological effects at spatial and temporal scales smaller than that

of the actual fisheries (Collie *et al.*, 2000; Kaiser *et al.*, 2000; but see Thrush *et al.*, 1998). Contrasting scales potentially obscure changes in benthic communities directly related to these fisheries. Our research is based on a long-term benthic research programme that happened to correspond to the actual extent of cockle-dredging in the western Dutch Wadden Sea (Figure 2; Piersma *et al.*, 2001; Van Gils *et al.*, 2006b).

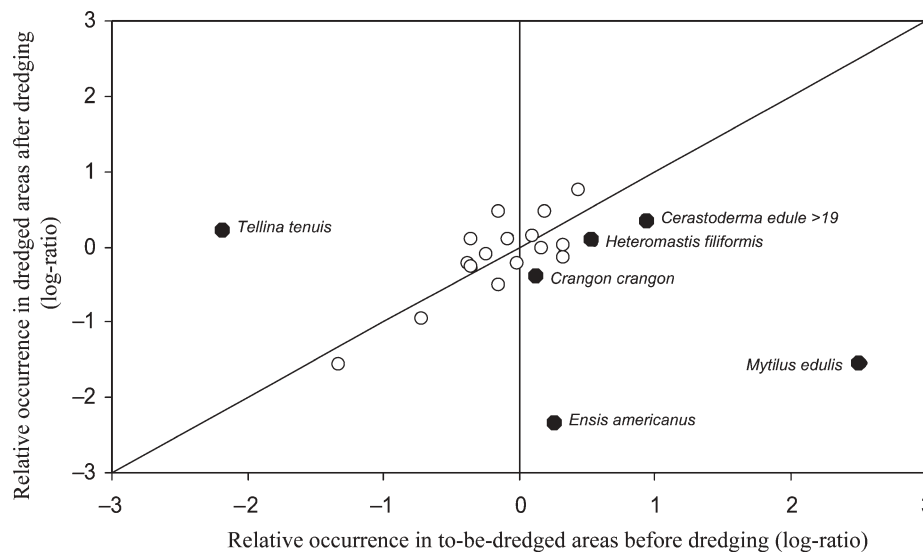
The experimental design that compared paired undredged and later dredged areas before and after dredging (Figure 2) to the best of our knowledge has not been used before on such a large scale and should allow assessment of short-term fishery effects. The paired areas were matched by location, height in the intertidal zone, and sediment characteristics, with the aim to minimize possible effects attributable to the non-random choice of fisheries locations. However, the possibility that areas selected by fisheries changed in a different way than unfished areas for other reasons than the fisheries itself cannot be excluded; changes may simply be related to the fact that the areas were biologically richer. Yet, under this constraint, we believe that our design is the best possible approach. The present analysis disentangled fisheries and natural mortality, and only the density change attributable to fisheries mortality is considered in relation to relative occurrence. This means that, in the absence of an effect of cockle-dredging, the relative occurrence and the fishery effect are the same ( $\ln N_{d0}/N_{c0} = \ln N_{d1}/N_{c1}$ ). To express the fisheries effect as the ratio of dredged-to-undredged densities before and after dredging ( $\ln N_{d0}/N_{c0} - \ln N_{d1}/N_{c1}$ ), though appealing, would produce spurious correlations when combined with relative occurrence ( $N_{d0}/N_{c0}$ ). This is because density changes consist of natural mortality plus recruitment in the undredged area and additional dredging mortality in the dredged area. Both these independent mortalities would be incorporated in the error of the relative occurrence and the fisheries effect.

Contrary to the general impression at the time (and see Beukema *et al.*, 1998, who refer to distinct cockle beds), mechanical dredging in the late 1990s focused on intertidal areas with the greatest abundance of large cockles (>19 mm) and the highest species diversity. Species targeted by shorebirds for food (*M. edulis*, *N. diversicolor*, *A. marina*, and *M. balthica*) were in greater densities in to-be-dredged than in undredged areas.

Although some species we observed were only present in modest densities in areas targeted by cockle-dredgers, short-term



**Figure 3.** Total number of species of macrozoobenthic animals at sampling stations (consumption-size cockles not included) in intertidal flat areas in the western Dutch Wadden Sea in 1998, 2000, 2001, and 2002, either affected (d) or not affected (c) by mechanical cockle-dredging (see Table 1 for species composition). The numbers on top of each box indicate the number of samples taken. Average (dot), median (horizontal line), and outliers (asterisk) are shown in the box-plot.



**Figure 4.** Responses of intertidal benthic species to mechanical cockle-dredging a year after being dredged. The relative occurrence in paired dredged and undredged areas is plotted against the relative occurrence in the same areas before dredging. Relative occurrence is expressed as the log-ratio of the average densities. Statistically significantly affected species are labelled (see Material and methods for statistical approach). The diagonal line differentiates the fisheries effect; species significantly below the line are negatively affected by fisheries. The vertical line indicates equal relative occurrence in to-be-dredged and undredged areas.

effects of dredging were noted. Because our estimates of short-term dredging disturbance are conservative, because of the rough assignments of dredged and non-dredged sampling locations (see Dutch cockle-dredging practice), and because we did not perform a random search for correlations but rather evaluated species one by one, we believe that application of a correction for multiple testing would lead to an unreasonable increase of type-II error (Nakagawa, 2004; Garamszegi, 2006). On longer time-scales, the dredged areas were characterized by reduced settlement of cockles (and *M. balthica*), which may relate to loss of fine silts and an increase in median grain size (Piersma *et al.*, 2001; Zwarts *et al.*, 2003). Changes in sediment composition influence the feeding performance of deposit-feeding bivalves (Drent *et al.*, 2004), including small cockles (Kang *et al.*, 1999; Rossi *et al.*, 2004). Such change in the sediment may also explain the increase in abundance of *Tellina tenuis* a year after being dredged. *T. tenuis* prefers very coarse sediments, often near the low water mark (Dekker and Beukema, 1999; own data). A previous meta-analysis on the impact of mechanical fisheries on non-target species also noted that species from coarser sediments were less likely to be affected (Collie *et al.*, 2000).

Using an overlapping dataset (1998–2002 rather than 1998–2003), but with different spatial resolution (272 km<sup>2</sup> blocks, rather than the 25 paired area comparisons used here), statistical technique and size assignment ( $\leq 16$  mm in Van Gils *et al.*, 2006b,  $\leq 19$  mm here), Van Gils *et al.* (2006b) also found densities of small cockles to remain stable in dredged blocks (note that we found a non-significant density increase; Table 1). Those authors showed that the detrimental effects of cockle-dredging on top predators such as red knots (*Calidris canutus*) was due to loss of body condition of cockles of edible size rather than to density changes.

Decreases of *C. edule* and *M. balthica*, attributable to a single-dredging event, occurred over many rather than single years, and were a consequence of decreased spatfall in the years following

dredging and increases in median grain size in the dredged area (Piersma *et al.*, 2001). The absence of a short-term dredging effect on *M. balthica*, as we found in our study, is indeed consistent with this. That these species continued to decline up to 8 years after dredging (Piersma *et al.*, 2001) suggests that single and multiple dredging events may reduce the system's resilience and shift intertidal soft-sediments to alternative states of reduced species richness (Scheffer *et al.*, 2001). The failure of seagrass (*Zostera noltii*) to re-establish, the ongoing decline of *M. balthica* numbers in the western Dutch Wadden Sea (own data), and the non-recovery of bivalve stocks after intensive cockle-dredging south of Vlieland and Richel (Piersma *et al.*, 2001) might be symptomatic of this state-shift.

To allow cockle-dredging, the Dutch government through its Ministry of Agriculture, Nature Conservation and Food Safety, had to give exemption from nature conservation laws, with due recognition of the precautionary principle and Ramsar's wise use principle. The compromise reached in parliament was that dredging for cockles should be allowed when more than 70% of the predicted energy intake of common eiders and European oystercatchers could be covered by the sum of the estimated availability of edible cockles, blue mussels, and trough shells (*Spisula subtruncata*) in the Wadden Sea and the nearshore waters of the North Sea. This requirement assumes that all biomass is harvestable (which it is not; Zwarts and Wanink, 1993), that birds are omniscient (which they may be; Van Gils *et al.*, 2006a) and free of travel costs (which they are not; Goss-Custard *et al.*, 2004; Van Gils *et al.*, 2006a), and that 30% of the required intake can be covered by other food sources (not a robust assumption according to Smit *et al.*, 1998; Camphuysen *et al.*, 2002; Atkinson *et al.*, 2003). These mollusc-eating birds are in greatest numbers in the Wadden Sea in their non-breeding season, which they have to survive in good condition to be able to complete their migration back to the breeding sites the following spring (Goss-Custard *et al.*, 2004; Van de Kam *et al.*, 2004).

The clear outcome of this work is to support the application of a whole ecosystem approach to fisheries management (e.g. Kaiser *et al.*, 2000; Murawski, 2000; Scheffer *et al.*, 2005), with application of the wise use principle as advocated by European legislation. This principle states that any economic activity should prove itself harmless before it is allowed. The following example is relevant for the Wadden Sea. The approval of cockle-dredging decreased numbers of small mussels *M. edulis* in the dredged intertidal areas (Figure 4). Consequently, the re-establishment of mussel beds in the western Dutch Wadden Sea was prevented (see also Herlyn and Millat, 2000; Hiddink, 2003), even though it represented a long-term conservation goal of the Dutch government (LNV, 1998).

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## References

- Abrahamse, J., Joenje, W., and Van Leeuwen-Seelt, N. (Eds). 1976. Waddenzee, natuurgebied van Nederland, Duitsland en Denemarken. Waddenvereniging, Harlingen/Natuurmonumenten, 's-Graveland. 372 pp.
- Atkinson, P. W., Clark, N. A., Bell, M. C., Dare, P. J., Clark, J. A., and Ireland, P. L. 2003. Changes in commercially fished shellfish stocks and shorebird populations in the Wash, England. *Biological Conservation*, 114: 127–141.
- Beukema, J. J., Cadée, G. C., and Dekker, R. 1998. How two large-scale "experiments" illustrate the importance of enrichment and fishery for the functioning of the Wadden Sea ecosystem. *Senckenbergiana Maritima*, 29: 37–44.
- Blundell, T. (Chair). 2004. Turning the tide: addressing the impact of fisheries on the marine environment. 25th Report from the Royal Commission on Environmental Pollution, London. 472 pp.
- Camphuysen, C. J., Berrevoets, C. M., Cremers, H. J. W. M., Dekinga, A., Dekker, R., Ens, B. J., van der Have, T. M., *et al.* 2002. Mass mortality of common eiders (*Somateria mollissima*) in the Dutch Wadden Sea, winter 1999/2000: starvation in a commercially exploited wetland of international importance. *Biological Conservation*, 106: 303–317.
- Coleman, F. C., and Williams, S. L. 2002. Overexploiting marine ecosystem engineers: potential consequences for biodiversity. *Trends in Ecology and Evolution*, 17: 40–44.
- Collie, J. S., Hall, S. J., Kaiser, M. J., and Poiner, I. R. 2000. A quantitative analysis of fishing impacts on shelf-sea benthos. *Journal of Animal Ecology*, 69: 785–798.
- Dayton, P. K. 2003. The importance of the natural sciences to conservation. *American Naturalist*, 162: 1–13.
- Dayton, P. K., Thrush, S. F., Agardy, M. T., and Hofman, R. J. 1995. Environmental effects of marine fishing. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 5: 205–232.
- De Vlas, J. 2000. Sporen kokkelvisserij. *Waddenbulletin*, 35: 19.
- Dekker, R., and Beukema, J. J. 1999. Relations of summer and winter temperatures with dynamics and growth of two bivalves, *Tellina tenuis* and *Abra tenuis*, on the northern edge of their intertidal distribution. *Journal of Sea Research*, 42: 207–220.
- Dijkema, R. 1997. Molluscan fisheries and culture in the Netherlands. Technical Report NMFS, 129: 115–135.
- Donkers, W. O. T. M. 1998. Kokkelvisintensiteit 1998 5. Report 87006-R01, DCI Meettechniek, Yerseke. 5 pp.
- Donkers, W. O. T. M. 2000. Kokkelvisintensiteit 1999 7. Report 07003-R01, DCI Meettechniek, Yerseke. 7 pp.
- Drent, J., Luttikhuisen, P. C., and Piersma, T. 2004. Morphological dynamics in the foraging apparatus of a deposit feeding bivalve: phenotypic plasticity and heritable effects. *Functional Ecology*, 18: 349–356.
- Ens, B. J. 2003. What we know and should know about mollusc fisheries and aquacultures in the Wadden Sea. In *Challenges to the Wadden Sea area*, Proceedings of the 10th International Scientific Wadden Sea Symposium, pp. 121–146. Ed. by W. J. Wolff, K. Essink, A. Kellermann, and M. A. Van Leeuwe. Ministry of Agriculture, Nature Management and Fisheries, and Department of Marine Biology, University of Groningen. 272 pp.
- Ens, B. J., Smaal, A. C., and de Vlas, J. 2004. The effects of shellfish fishery on the ecosystems of the Dutch Wadden Sea and Oosterschelde. Final Report on the Second Phase of the Scientific Evaluation of the Dutch Shellfish Fishery Policy (EVA II). Alterra-rapport 1011, RIVO-rapport C056/04, RIKZ-rapport RKZ/204.031. Alterra, Wageningen. 212 pp.
- Garamszegi, L. Z. 2006. Comparing effect sizes across variables: generalization without the need for Bonferroni correction. *Behavioral Ecology*, 17: 682–687.
- Goss-Custard, J. D., Stillman, R. A., West, A. D., Caldow, R. W. G., Triplet, P., dit Durell, S. E. A. le V., McGrorty, S., *et al.* 2004. When enough is not enough: shorebirds and shellfishing. *Proceedings of the Royal Society of London B*, 271: 233–237.
- Herlyn, M., and Millat, G. 2000. Decline of the intertidal blue mussel (*Mytilus edulis*) stock at the coast of Lower Saxony (Wadden Sea) and influence of mussel fishery on the development of young mussel beds. *Hydrobiologia*, 426: 203–210.
- Hiddink, J. G. 2003. Effects of suction-dredging for cockles on non-target fauna in the Wadden Sea. *Journal of Sea Research*, 50: 315–323.
- Huijssen, P. 2001. Kokkelvisintensiteit 2000 7. Report 01032-R01, DCI Meettechniek, Yerseke. 7 pp.
- Jackson, J. B. C. 2001. What was natural in the coastal oceans? *Proceedings of the Natural Academy of Sciences*, 98: 5411–5418.
- Jennings, S., and Kaiser, M. J. 1998. The effects of fishing on marine ecosystems. *Advances in Marine Biology*, 34: 201–352.
- Jones, J. B. 1992. Environmental impacts of trawling of the seabed: a review. *New Zealand Journal of Marine and Freshwater Research*, 26: 59–67.
- Kaiser, M. J., Clarke, K. R., Hinz, H., Austen, M. C. V., Somerfield, P. J., and Karakassis, I. 2006. Global analysis of response and recovery of benthic biota to fishing. *Marine Ecology Progress Series*, 311: 1–14.
- Kaiser, M. J., Ramsay, K., Richardson, C. A., Spence, F. E., and Brand, A. R. 2000. Chronic fishing disturbance has changed shelf sea benthic community structure. *Journal of Animal Ecology*, 69: 494–503.
- Kamermans, P., Schuiling, E., Baars, D., and Van Riet, M. 2003. Eindrapport EVA II (evaluatie schelpdiervisserij tweede fase). Deelproject A1: Visserij-inspanning. RIVO-rapport C057/03, Yerseke. 97 pp.
- Kamermans, P., Smaal, A. C., and Nakagawa, A. C. 2002. Mussel culture and cockle fisheries in the Netherlands: finding a balance between economy and ecology. *Journal of Shellfish Research*, 21: 509–517.



- Kang, C. K., Sauriau, P.-G., Richard, P., and Blanchard, G. F. 1999. Food sources of the infaunal suspension feeding bivalve *Cerastoderma edule* in a muddy sandflat of Marennes-Oléron Bay, as determined by analyses of carbon and nitrogen stable isotopes. *Marine Ecology Progress Series*, 187: 147–158.
- Kareiva, P., and Laurance, W. F. 2002. Dutch Wadden Sea might not be doing so well. *Trends in Ecology and Evolution*, 17: 163.
- LVN (Ministry of Agriculture, Nature Conservation and Fisheries/Food quality). 1998. Structuurnota Zee- en kustvisserij: Evaluatie van de maatregelen in de kustvisserij gedurende de eerste fase (1993–1997) (Report). Den Haag, Groningen, maart 1998. 35 pp.
- Manly, B. F. J. 1997. Randomization, Bootstrap and Monte Carlo Methods in Biology, 2nd edn. Chapman and Hall, London. 455 pp.
- Murawski, S. A. 2000. Definitions of overfishing from an ecosystem perspective. *ICES Journal of Marine Science*, 57: 649–658.
- Nakagawa, S. 2004. A farewell to Bonferroni: the problems of low statistical power and publication bias. *Behavioral Ecology*, 15: 1044–1045.
- Piersma, T., Dekinga, A., and Koolhaas, A. 1993a. Een kwetsbare keten: modder, nonnetjes en kanoeten bij Griend. *Waddenbulletin*, 28: 144–149.
- Piersma, T., Hoekstra, R., Dekinga, A., Koolhaas, A., Wolf, P., Battley, P., and Wiersma, P. 1993b. Scale and density of intertidal habitat use by knots *Calidris canutus* in the western Wadden Sea in relation to food, friends and foes. *Journal of Sea Research*, 31: 331–357.
- Piersma, T., and Koolhaas, A. 1997. Shorebirds, shellfish(eries) and sediments around Griend, Western Wadden Sea, 1988–1996. NIOZ-rapport 1997-7, Texel. 118 pp.
- Piersma, T., Koolhaas, A., Dekinga, A., Beukema, J. J., Dekker, R., and Essink, K. 2001. Long-term indirect effects of mechanical cockle-dredging on intertidal bivalve stocks in the Wadden Sea. *Journal of Applied Ecology*, 38: 976–990.
- R Development Core Team. 2006. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0. <http://www.R-project.org>.
- Roberts, C. M. 1997. Ecological advice for the global fisheries crisis. *Trends in Ecology and Evolution*, 12: 35–38.
- Rosenberg, A. A. 2003. Managing to the margins: the overexploitation of fisheries. *Frontiers in Ecology*, 1: 102–106.
- Rossi, F., Herman, P. M. J., and Middelburg, J. J. 2004. Interspecific and intraspecific variation of delta 13C and delta 15 N in deposit- and suspension-feeding bivalves (*Macoma balthica* and *Cerastoderma edule*): evidence of ontogenetic changes in feeding mode of *Macoma balthica*. *Limnology and Oceanography*, 49: 408–414.
- Scheffer, M., Carpenter, S., and de Young, B. 2005. Cascading effects of overfishing marine systems. *Trends in Ecology and Evolution*, 20: 579–581.
- Scheffer, M., Carpenter, S., Foley, J. A., Folke, C., and Walker, B. 2001. Catastrophic shifts in ecosystems. *Nature*, 413: 591–596.
- Smit, C. J., Dankers, N., Ens, B. J., and Meijboom, A. 1998. Birds, mussels, cockles and shellfish fisheries in the Dutch Wadden Sea: how to deal with low food stocks for eiders and oystercatchers? *Senckenbergiana Maritima*, 29: 141–153.
- Swart, J. A. A., and Van Andel, J. 2007. Rethinking the interface between ecology and society. The case of the cockle controversy in the Dutch Wadden Sea. *Journal of Applied Ecology*, 44, doi: 10.1111/j.1365-2664.2007.01366.x.
- Thrush, S. F., Hewitt, J. E., Cummings, V. J., Dayton, P. K., Cryer, M., Turner, S. J., Funnell, G. A., et al. 1998. Disturbance of marine benthic habitat by commercial fishing: impacts at the scale of the fishery. *Ecological Applications*, 8: 866–879.
- Turner, S. J., Thrush, S. F., Hewitt, J. E., Cummings, V. J., and Funnell, G. 1999. Fishing impacts and the degradation or loss of habitat structure. *Fisheries Management and Ecology*, 6: 401–420.
- Van de Kam, J., Ens, B., Piersma, T., and Zwarts, L. 2004. Shorebirds: an illustrated behavioural ecology. KNNV Publishers, Utrecht. 368 pp.
- Van Gils, J. A., Dekinga, A., Spaans, B., Vahl, W. K., and Piersma, T. 2005. Digestive bottleneck affects foraging decisions in red knots *Calidris canutus*. 2. Patch choice and length of working day. *Journal of Animal Ecology*, 74: 120–130.
- Van Gils, J. A., Piersma, T., Dekinga, A., Spaans, B., and Kraan, C. 2006b. Shellfish dredging pushes a flexible avian top predator out of a marine protected area. *Public Library of Science—Biology*, 4: 2399–2404.
- Van Gils, J. A., Spaans, B., Dekinga, A., and Piersma, T. 2006a. Foraging in a tidally structured environment by red knots (*Calidris canutus*): ideal, but not free. *Ecology*, 87: 1189–1202.
- Watling, L., and Norse, E. A. 1998. Disturbance of the seabed by mobile fishing gear: a comparison to forest clearcutting. *Conservation Biology*, 12: 1180–1197.
- Wolff, W. J. (Ed.) 1983. *Ecology of the Wadden Sea*. Balkema, Rotterdam. 2132 pp.
- Zwarts, L., Dubbeldam, W., van den Heuvel, H., van de Laar, E., Menke, U., Hazelhoff, L., and Smit, C. J. 2003. Bodemgesteldheid en mechanische kokkelvisserij in de Waddenzee130. Rapport G (EVA-II), RIZA, Lelystad. 130 pp.
- Zwarts, L., and Wanink, J. H. 1993. How the food supply harvestable by waders in the Wadden Sea depends on the variation in energy density, body weight, biomass, burying depth and behaviour of tidal-flat invertebrates. *Journal of Sea Research*, 31: 441–476.

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